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Target Parameter Estimation with Distributed Sensors

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1. Summary of Work.

1.1. Background

The primary focus of this research was the problem of detecting targets and estimating their locations with sensor arrays. Particular attention was paid to the performance requirements in the strategic defense scenario which dictated high probability of detection and high accuracy in localization in the presence of coherent interference. As the luxury of off-line computation was not available, computational efficiency in algorithm design was stressed. Since the sensors may be geographically distributed, the problem of distributed computing and computational resource allocation were also addressed. Statistical algorithms that were considered in this regard, for example hidden Markov model-based algorithms were also used for problems in vision and pattern recognition The theoretical developments have extended our understanding of the degree of data-reduction, without loss of information as a preprocessor for detection and estimation. The new algorithms have generalized signal-subspace detectors/estimators to beamspace and wideband processing. Neural network formalism was also used both for the estimation problem and for issues related to the channel bandwidth allocation and storage The most significant developments of our research are summarized below. Details of these results can be found in the publications that were fully or partially supported by this grant. These are listed in Section 2.

1.2. Detection and Estimation with Sensor Arrays

i) Data reduction for wideband array processing [1]. In many nonlinear parameter estimation problems, the size of the data is too large for the implementation of an optimum parameter estimator, for example based on the maximum-likelihood principle. Many practical algorithms, therefore, begin by forming a statistic of the data with substantially smaller dimension than the original data, and structuring a suboptimum estimator based on this reduced data. Of course, if the reduced data is a sufficient statistic, no information is lost and in principle the optimum estimator may be implemented in terms of the lower-dimensional data. We have investigated the degree of sufficiency of the coherently averaged spatial covariance matrix for wideband sources, when the directions of arrivals of these sources are estimated by a wideband sensor array. A measure of sufficiency was formulated on the basis of the Fisher's information matrices for narrow sub-band data as well as the coherently-averaged covariance matrix.

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ii) Sensor-efficient algorithms [2]. Several results have been obtained on the performance of a sensor-efficient algorithm for the estimation of the directions of multiple targets. This system requires multiple frequency operation. The frequencies are spaced in a manner to effectively yield multi-sensor operation with only two sensors. Thus, it is possible to estimate the directions of arrival of multiple targets with ony two sensor elements. The algorithm and some performance results are described in.

iii) Adaptive subspace estimation [3]-[8]. Adaptive signal-subspace techniques such as MUSIC and Minimum-Norm are examples of "super-resolution" techniques for the estimation of frequencies of sinusoids or directions of arrival (doa) of emitter signals by an array of sensors. Implementations of these techniques, however, have been based on batch estimation of the eigenvectors of the signal covariance matrix making them unsuitable for adaptive processing that is needed for the tracking of non-stationary signal parameters. A notable exception is an algorithm presented by Thompson for adaptive estimation of the eigenvector corresponding to the smallest eigenvalue of the nonstationary sample covariance matrix, leading to an adaptive implementation of the Pisarenko estimator. Some of these techniques and their extensions and modifications have been used by practitioners in the sonar and radar research communities such as Dr. Owsley Dr. Kesh Bakhru or Cubic Defense Systems. We have collaborated with Dr. Bakhru in comparing a method proposed by them with our subspace estimators.

We have formulated several adaptive estimators, and their practical implementations, of the complete noise- or signal-subspace. For an L-element array and d sources, for examples, these algorithms adaptively estimate the eigenvectors corresponding to either the smallest L-d or the largest d eigenvalues of a continuously updated sample covariance matrix. The major advantage of this approach, which is a generalization of Thompson's technique, is that it can be used with methods such as MUSIC which are known to perform substantially better than Pisarenko's technique in estimating frequencies or doa's that change with time. These subspace estimation algorithms have additionally been extended to algoritms for on-line tracking of the roots of spectral polynomials that arise in the root versions of high-resolution doa estimators

iv) Generalized Coherent Signal-Subspace estimation and estimator performance [9]-[12]. The Coherent Signal-Subspace Method (CSM) is a computationally manageable general approach to the problem of detection, direction of arrival (doa) estimation and beamforming for wideband co-channel signals by a sensor array. This approach requires the design of so-called focusing matrices for transorming the covariance matrices of the constituent narrowband sub-channels into a single frequency-=averaged effective covariance matrix at the channel center frequency. The original CSM was generalized to a wider class of array geometries and signal and noise models. These include a coherent ESPRIT algorithm for the wideband case as well as the CSM for spatially and spectrally non-white noise. New statistical results were also obtained for detection and estimation using the narrowband signal-subspace and the coherent signal subspace algorithms. These have led to work by several other authors on the subject of theoretical detector and estimator performance evaluations.

v) Multi-group Coherent Signal-Subspace processing [13]. Much effort was expended in determining frequency domain focusing strategies for the case in which signals arrive from widely separated groups of closely-spaced sources. The criteria of interest were statistical reliability of detectors and estimators as well as threshold extension through coherent averaging of narrowband covariance matrices. The RSS transformation matrix requires the computation of singular vectors for all the frequency bins. Thus, we considered other possibilities for accomplishing the focusing effectively and computationally more efficiently. For larger arrays (16 elements or more) one possibility is to perform focusing of subspaces in single-group sectors. We have devised a sector focused CSS procedure that requires the very simple diagonal transformation matrices for appropriately defined sectors of the observation space. We have also determined computationally efficient transformation matrices for multigroup problems, that may also be used with a small number of elements.

vi) CSM and the Wideband Maximum Likelihood approach. Formulations of the narrowband Maximum-Likelihood Estimator (MLE) may be extended to the wideband case. One drawback of the MLE is that it involves iterative solutions of highly non-linear equations. Another drawback of the approach is that the number of sources must be known and reasonably good initial estimates be available. Nevertheless, due to the optimality of MLE it is desirable it is desireable to use this method perhaps as a fine-tuning post-processor for a computationally efficient suboptimum initial estimator with low threshold of resolution. For example, the MLE for two closely spaced sources, requires some thirty iterations to coverage. It is computationally an order of magnitude more intensive than CSM. It does, however, produce estimates that have smaller bias and variance than the CSM. If accuracy of the order produced by the MLE is required, we have shown that one may use CSM to determine the number of sources and generate good initial estimates. This is then effectively followed by a few iterations of the MLE algorithm.

vii) Time-domain realization of the CSS transformations [14]-[18]. One of the major results obtained with respect to practical wideband array processors has been the developments of several time-domain pre-processors so that focusing is accomplished without a need for frequency decomposition. These can be used for adaptive update of the directions-of-arrival of moving wide-band sources, as well as for beamforming in the presence of coherent interference. Several coupled FIR filter realizations of the CSS transformations were devised and implemented. One class of these approximate structures is based on the Taylor series expansions of the transfer function matrices in the neighborhood of the center frequency of operation. Lowpass versions of these were also derived that operate on the complex envelope of the received signal vector. The performance of these processors has been shown to be nearly as good as the frequency-domain CSS processors. The Taylor series approach, however, cannot be used to approximate the RSS class of focussing matrices.

The above-mentioned CSM focusing preprocessors were in the form of multichannel FIR filters. These were then designed directly as filters approximating frequency domain focusing transfer function matrices. Our later work was concerened with the design of such filters directly in terms of information about the locations of the groups of sources. A least-squares subspace fitting approach was developed which is cast in the form of constrained matrix fitting with a solution which is a generalization of the Orthogonal Procrustes problem. Results comparable to the frequency-domain RSS for multigroup scenarios were obtained.

viii) Coherent Signal-Subspace processing in a sector [19]. Much effort in this work was expended in determining focusing matrices for the case in which signals arrive from widely separated groups of closely spaced sources (multigroup case). For moderate or large number of sensors, beam-space processing has been found useful in narrowband direction finding. We have used the approach suggested by Forster and Vessozi for narrowband arrays, in conjunction with the CSM method. We have demonstrated that selecting a sector that contains a group of sources of interest, via Discrete Prolate Spheroidal Sequence (DPSS) weighting, effectively removes the interfering groups and makes the CSM with the very simple diagonal focusing matrix perform as well as the more complicated Rotational Signal-Subspace (RSS) focusing operation. The wideband maximum-likelihood algorithm of Bohme was also implemented in the sector which is formed by the DPSS weights and shown to slightly improve the CSM estimates. Therefore for larger arrays, this approach complements the RSS.

ix) Broad-band beam-space source localization [20]-[22]. A significant study of the use of beam-space preprocessing (i.e., spatial-filtering and observation dimension reduction) for broad-band source localization was carried out by K. M. Buckley and his students. Potential advantages of beam-space preprocessing which motivated this study are: computation reduction; improvement in source location estimation performance for some types of estimators; and reduction in sensitivity to noise covariance structure.

Several of the contributions were:

a) broad-band preprocessor structure definition;

b) beam-space preprocessor evaluation;

c) beam-space preprocessor design;

d) statistical and empirical performance analysis of narrow-band and broad-band beam-space spatial-spectrum estimators; and

e) performance analysis of narrow-band and broad-band beam-space maximum likelihood and least-squares source location estimators.

x) Spatial-spectrum estimation in a location sector [23]. A new eigenspace-based approach to spatial-spectrum estimation for arbitrarily configured arrays which employs projections onto a particular vector or vector set in the estimated noise-only subspace. The vector or vector set is one which is, in some sense, closest to the section of the array manifold corresponding to a source location sector of interest. The approach is applicable to both narrowband and broad-band problems. The novelty and significance of this new approach is twofold. First, this CLOSEST approach is a new full-dimensional element-space approach to spatial-spectrum estimation. It incorporates *prior* knowledge of the array manifold over a location sector of interest to provide SNR spectral-resolution thresholds and location estimation variances which are lower than those of MUSIC and MIN-NORM. For some arrays, these can be substantially lower. Second, by establishing a relationship between a new CLOSEST estimator and spatial-spectrum estimation in a reduced-dimension beam-space,we reveal the mechanism behind which (as recently observed) beam-space processing with MUSIC provides spectral-resolution thresholds which are lower than those of MUSIC and MIN-NORM in element-space.

xi) Weighted-Norm MUSIC [24], [25]. A signficant development in the later stages of this project was the discovery and development of a new paradigm for signal-subspace estimator design. This approach uses a generalized distance between functionals of vectors in certain subspaces of the signal subspace. The computational load of this method is similar to MUSIC. Its threshold performance, however, is significantly superior to that of MUSIC and similar techniqes. Further design of estimators and the evaluation of the properties of such estimators and their allied robust detectors are in progress.

ix) Neural networks for direction finding [26]-[29]. Three neural net architectures were utilized for direction finding applications. The first is based on a modification of Hopfield's net and is designed for both narrowband and wideband and coherent scenarios [goryn]. This approach is characterized by computational load on the same order as nonlinear least-squares and requires the computation of weights for each set of snapshots. The second network is based on the multilayer perceptron concept and has been formulated for narrowband direction finding. This approach requires very extensive training. The training, however, is accomplished off-line and with the help of a powerful computer or a parallel processor. The search during the presentation of new set of data is almost instantaneous.

The third network is formulated as an analog recurrent network to solve the direction-finding problem based on the optimality criterion of fitting the data to a covariance model. The discovery of this network was important for several reasons. The network which was originally proposed by Hartline and Ratliff for modeling an elementary vision system, is not well-known by signal processors. This network, however, can be cast in a form to solve difficult numerical problems such as one presented by the solution of the least-squares covariance model fitting approach resulting from a general direction-finding algorithm proposed by D'Assumpcao. Our formulation results in a feedback network with weights that are independent of the data and that can be precomputed. We have shown that the input to the network can be reduced to the output of any power spectrum estimator such as a conventional beamsum or Capons MLM. The computationally efficient algorithm is not as high in resolution as eigen-based estimators. It is, however, robust in that it can operate with nonwhite and non-Gaussian noise, coherent sources and , for well-separated sources, with fewer sensors than sources--all possibilities in difficult and changing environments.

Later work on the dynamic equations of the Hartline-Ratliff network have resulted in faster convergence and more accurate solutions in difficult cases such as resolution of closely-spaced sources of radiation received by an array of sensors. We have also recently shown that this network results from a limiting form of a Hopfield network with a saturating linear activiation function. The network can be used for solving general ill-conditioned signal recovery problems such as the restoration of images which are linearly blurred and degraded by noise. The data-independence of the weights for this network is a major advantage of this new scheme over estimators based on the Hopfield net that were previously proposed by investigators, including the author.

1.3 Communications and Related Problems

In the following, the research activities in reliable communications by Dr. N. K. Huang are summarized under three topics: anti-jamming/anti-interception, distributed information processing and image analysis. Dr. Huang's involvement in this contract ended in 1989.

i) Anti-jamming/anti-interception [30]-[31]. We have studied statistical methods to define (pseudo-) structures of the seemingly unstructured randomness. When this randomness is from an intelligent jammer, knowing this rule of generating random signals helps to decide on a counter-measure We have also looked at ways to trade some processing gain for communication security in a code-division multiple access system. Our conclusion is that at high signal-to-noise ratio, in exchange of immunity to interception, up to one sixth of the processing gain can be sacrificed with little degradation of the system performance otherwise.

ii) Distributed information processing [32]-[36]. We have carried out performance analysis and considered issues regarding implementation with neural networks. Previous studies considered the performance as a function, in addition to traffic pattern, the bandwidth of the channels and the uncertainty of the distributed network status at individual nodes. We have used a neural network model for bandwidth allocation and have studied more fundamental properties of neural properties of neural networks. The upper bound on the number of dichotemies of multi-level threshold function was the best bound in 1989.

iii) Analysis of image textures. [37]-[39]. Knowledge of textural regions in an image helps interpret the content of the scene and locate the objects of interest. Natural textures also serve as an abundant source for the study of a variety of random signals. Techniques developed for texture segmentation, for instance, are readily applicable to discriminating the nonstationarity of signals, which is the basis for channel characterization problems and traffic pattern analysis, and is therefore directly related to the other topics (adaptive anti-jamming/anti-inspection and distributed information processing) we have studied under this grant in the context of reliable communication.

2. List of Publications.

1. "On the Statistical Efficiency of the Coherently Averaged Covariance Matrix for the Estimation of the Parameters of Wideband Sources", Proc. ICASSP '87, Dallas.

2. "Sensor-Efficient Array Processing", T. Cichocki and M. Kaveh, in Acoustical Imaging, Vol. 15, 1987.

3. "Wideband Adaptive Arrays Based on the Coherent Signal-Subspace Transformation", Proc. ICASSP '87, Dallas.

4. "Adaptive Signal-Subspace Algorithms for Frequency Estimation and Tracking," Proc. ICASSP '87, Dallas.

5. "Adaptive Eigen-Subspace Methods for Direction and Frequency Estimation and Tracking," J. F. Yang and M. Kaveh, IEEE Trans. on ASSP, February, 1988.

6. "Adaptive Algorithms for Tracking the Roots of Spectral Polynomials," J. F. Yang and M. Kaveh, Proc. ICASSP89, May 1989, Glasgow, Scotland.

7. "Parallel Adaptive Rooting Algorithms for General Frequency Estimation and Tracking," IEE Proceedings Part F, February 1992.

8. "Coherent Signal-Subspace Transformation Beamformer," J. F. Yang and M. Kaveh, Proceedings of IEE, part F, July 1990.

9. "Coherent Wideband ESPRIT Method for Directions of Arrival Estimation of Multiple Sources," H. Hung and M. Kaveh, IEEE Trans. on ASSP, February 1990.

10. "On the Theoretical Performance of a Class of Estimators of the Number of Narrowband Sources", M. Kaveh, H. Wang and H. Hung, IEEE Trans. on ASSP, September 1987.

11. "On the Performances of Signal-Subspaces Processing-PartII - Coherent Wideband Systems", H. Wang and M. Kaveh, IEEE Trans. on ASSP, October 1987.

12. "Threshold Properties of Narrowband Signal-Subspace Estimators", M. Kaveh and H. Wang, chapter in Nonlinear Spectrum Estimation, S. Haykin editor, Prentice Hall, 1991.

13. "Focusing Matrices for Coherent Signal-Subspace Processing," H. Hung and M. Kaveh, IEEE Trans. on ASSP, August 1988.

14. "Time-Domain Wideband Direction Finding Using Coherent Signal-Subspace Transformations," S. Sivanand, J. F. Yang and M. Kaveh, IEEE Trans. on ASSP, February 1991.

15. "Coherent Signal-Subspace Transformation Beamformer," J. F. Yang and M. Kaveh, Proc. IEE, part F, August 1990.

16. "Focusing Filters for Wideband Direction Finding," S. Sivanand, J. F. Yang and M. Kaveh, IEEE Trans. on ASSP, February 1991.

17. "Multichannel Filtering for Wideband Direction Finding," S. Sivanand and M. Kaveh, IEEE Trans. on Signal Processing, September 1991.

18. "Broadband Focusing for Partially Adaptive Beamforming," S. Sivanand and M. Kaveh, IEEE Trans. on Aerospace and Electronic Systems, to appear 1993.

19. "Coherent Signal Subspace Processing in a Sector," A. Bassias and M. Kaveh, IEEE Trans. on Systems, Man and Cybernetics, September, 1990.

20. "Maximum likelihood and least-squares broadband source localization in beam-space," X. L. Xu and K. M. Buckley, 22-nd Annual Asilomar Conference on Circuits, Systems, and Computers, Nov. 1988.

21. "A statistical performance comparison of MUSIC in element-space and beam-space," X. L. Xu and K. M. Buckley, Proc. ICASSP '89, pp. 2124-2127, May 1989.

22. "Reduced dimension beam-space broad-band source localization: preprocessor design," K. M. Buckley and X. L. Xu, 33-rd Annual SPIE Conference, pp. 358-367, Aug. 1988.

23. "Spatial-spectrum estimation in a location sector," K. M. Buckley and X. L. Xu, IEEE Trans. on ASSP, November 1990 .

24. "Threshold extension based on a new paradigm for MUSIC-type estimation." M. Kaveh and A. Bassias, Proceedings of ICASSP 90, Albuquerque NM, April 1990.

25. "Rethinking the formulation of signal-subspace parameter estimators," M. Kaveh, Proc. IFAC Symposium on Identification, Budapest, Hungary, July, 1991.

26. "Conjugate Gradient Learning Algorithms for the Multilayered Perceptron," D. Goryn and M. Kaveh, Proc. 1989 Midwest Circuits and Systems Conference, Aug. 1989.

27. Sensor Array Processing with Artificial Neural Networks. D. Goryn and M. Kaveh, in Spectral Analysis in One or Two Dimensions, S. Prasad and R. L. Kashyap eds., Oxford & IBH Publishing Co. New Delhi, 1991.

28. "Multilayered perceptrons for narrowband direction finding," D. Goryn and M. Kaveh, Proceedings of EUSIPCO, September 1990, Barcelona Spain.

29. "Direction finding networks based on the approximate maximum likelihood and covariance fit formulations," D. Goryn and M. Kaveh, in Proc. ICASSP '91.

30. "Extracting Information from Apparent Randomness in Cardiovascular Data," N.K. Huang, The Tenth Annual International Conference of the IEEE Engineering in Medicine and Biology Society, New Orleans, Louisiana, November 5, 1988.

31."CDMA Communication Networks and Applications to Data Acquisition, Monitoring and Security," N.K. Huang, Network Workshop, Minneapolis, Minnesota, November 10, 1988.

32. "A case study of solving optimization problems using neural networks," X. Xu, W.T. Tsai, N.K.Huang, Journal of Neural Networks, Vol.1, Supp.1, 1988, p.151

33. "Bounds on capacity of multi-threshold network," I. Bentov, N.K. Huang, Journal of Neural Networks, Vol.1, Supp.1, 1988, p.74

34. "A generalized neural network model, ," X. Xu, W.T. Tsai, N.K. Huang, Journal of Neural Networks, Vol.1, Supp.1, 1988, p.150

35. "On information capacity of Hopfield's model, " X. Xu, W.T. Tsai, N.K. Huang, Journal of Neural Networks," Vol.1, Supp.1, 1988, p.149.

36. "Dynamic load balancing at individual nodes in LAN," N. K. Huang, Proc. of SPIE/IST, Vol. 876, 1988

37. "Segmentation using textural energy," X. Gong, N.K. Huang, Proceedings of International Conference of Pattern Recognition, Rome, Italy, November 1988.

38. "Classification of natural textures by entropy of a Markov chain," N.K. Huang, X.Gong, Proceedings of Symposium of Information Theory and Applications, Beppu, Japan, December 1988.

39. "Textured image recognition using Hicden Markov Model," X. Gong, N.K. Huang, Proceedings of ICASSP-88.